Numerical Simulation of Global Temperature Change during the 20th Century with the IAP/LASG GOALS Model

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ABSTRACT

The IAP/LASG GOALS coupled model is used to simulate the climate change during the 20th century using historical greenhouse gases concentrations, the mass mixing ratio of sulfate aerosols simulated by a CTM model, and reconstruction of solar variability spanning the period 1900 to 1997. Four simulations, including a control simulation and three forcing simulations, are conducted. Comparison with the observational record for the period indicates that the three forcing experiments simulate reasonable temporal and spatial distributions of the temperature change. The global warming during the 20th century is caused mainly by increasing greenhouse gas concentration especially since the late 1980s; sulfate aerosols offset a portion of the global warming and the reduction of global temperature is up to about 0.11°C over the century; additionally, the effect of solar variability is not negligible in the simulation of climate change over the 20th century.

Key words: global warming, greenhouse gases, sulfate aerosols, solar variability

1. Introduction

Human activity changes the earth's climate system in various ways. The most striking phenomenon is that the concentrations of greenhouse gases have increased since the latter part of the nineteenth century. Observations indicate that the concentration of carbon dioxide has increased to roughly 370 ppm from 280 ppm before the industrial revolution. In the meantime, observed global mean temperature has also increased gradually by about 0.6°C in the past 100 years, with paleoclimate data indicating that this is the warmest century in the past 1000 years (Mann et al., 1998). There is increasingly strong evidence that the warming of the 20th century is probably caused by the increasing concentration of greenhouse gases. At present with the development of the world economy and increasing population, the concentration of greenhouse gases continues to rise. Global warming is becoming an important social issue as well as being of scientific interest.

Climate models serve as useful tools for studying past global warming. Since the middle 1990s, research has been underway to reproduce the climate change over the 20th century with the input of the historical greenhouse gases concentration including CO_2 and other major gases such as CH_4, N_2O, etc. This serves not only in model validation, but also forms the basis of predicting future climate change.

Previous climate model results indicate that global mean temperature change during the 20th century is overestimated if only the greenhouse gases are considered. However, the simulated temperature is much closer to observations if the effect of sulfate aerosols is included (e.g., Meehl et al., 1996). The reason is that the radiative forcing of sulfate aerosols is opposite to that of greenhouse gases, and so partly offsets the greenhouse effect. In recent years, several studies have been done to simulate the climate variation over the 20th century with coupled models. It is necessary to make a comparison of the results from different models in order to reduce the uncertainty of the models (Lambert and Boer, 2001). There is little of this kind of work in China, especially using Chinese models

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to investigate climate change induced by both greenhouse gases and sulfate aerosols. In the present work we use the IAP/LASG GOALS coupled model developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences. The model was improved to include the addition of chlorofluorocarbons (CFCs) and inclusion of the effect of sulfate aerosols. The effect of solar variability is also included in the model so as to study the effect of natural climate forcing. This is of importance for detecting the anthropogenic signal from observations. The climate variation over the 20th century is simulated and compared with observations. The structure of this paper is organized as follows: the first section introduces the model improvements, the second section describes the experimental design; the third section discusses the main results; and the last section provides the conclusions and discussion.

2. The model

2.1 *Model description*

The GOALS model is a global ocean atmosphere land system coupled model described in Wu et al. (1997) and Zhang et al. (2000). The atmospheric component of the coupled model is a spectral model with a rhomboidal truncation at a zonal wave number of fifteen (R15), with a corresponding surface grid of about 7.5°lat×4.5°lon. There are 9 levels in the vertical. The oceanic component of the GOALS model is a primitive equation grid-point model with 5°lat×4°lon horizontal resolution. There are twenty unevenly-spaced layers in the vertical direction with η–coordinates. The land process model is a simplified version of the SiB model, which includes three soil layers and one vegetation layer with twelve types of vegetation (Xue et al, 1991). The coupling between the oceanic component and atmospheric component takes into account the exchange of heat flux and momentum flux, and the coupling scheme used in the GOALS model is the modified monthly flux anomaly exchange (MMFA) scheme (Yu and Zhang, 1998).

The GOALS model was previously used to simulate the climate change with CO_2 increasing at a rate of 1% yr^{-1} (Guo et al., 2001). The simulated global mean surface air temperature change at the time of CO_2 doubling is 1.65°C, which is close to the average of 19 models reported in the IPCC TAR report (2001). That work considered CO_2 only rather than individual greenhouse gases, and the direct effect of sulphate aerosols was not included.

2.2 *Improverent of the model*

The major improvement to the model involved the introduction of the direct effect of sulfate aerosols with the explicit consideration of direct scattering of sulfate aerosols. This is considered superior to other simpler schemes in which the scattering of sulfate aerosols is represented simply by increasing the surface albedo. Additional improvement includes the addition of industrial gases (CFC-11 and CFC-12), which has been found to be important in reproducing the climate change since the 1960s as realistically as possible. So the current version includes almost all well-mixed greenhouse gases, and their effects are explicitly represented.

2.2.1 *Inclusion of industrial greenhouse gases*

In the radiation scheme of GOALS, a k-distribution method was used to calculate atmospheric transmissivity. The absorbing gases include CO_2, CH_4, and N_2O, etc. We have added CFC-11 and CFC-12 into the model. Compared with CO_2, CH_4, and N_2O, the total burden of CFCs in the air is much less, and their radiative forcing is a small portion of the total radiative forcing of the greenhouse gases. However, we included them in the model because CFCs are the gases emitted completely by industrial activities, so representation of CFCs in the model is of importance to assess properly the effect of anthropogenic emission especially since the 1960s when large amounts of industrial CFCs began to be used widely. Also, the inclusion of CFCs allows us to have almost all of the greenhouse gases available, so as to provide an easy path for upcoming research for other model users.

The absorption coefficient k of various kinds of gases is generally calculated by using their spectrum data. As there is no spectrum data for CFCs available, the absorption cross section taken from HITRAN96 was applied to obtain their absorption coefficients (Ma, 2002).

2.2.2 *Explicit representation of the scattering of sulfate aerosols*

The direct effect of sulfate aerosols operates by scattering solar radiation back to space, in a manner roughly equivalent to an increase in the planetary albedo. As a result, many researchers have used a simple scheme to represent the direct effect of sulfate aerosols by increasing surface albedo. Because of its simplicity, this scheme has been widely applied to study the climatic effect of sulfate aerosols. However, this method takes sulfate aerosols as a thin layer near the surface, regardless of its vertical variation. There is generally a large relative humidity near the surface so a problem with this method is the overestimation of the direct radiative forcing (Mitchell et al., 1995)

In this work the direct effect of sulfate aerosols is accounted for by their radiative properties, which allows us to account for the spatial distribution of the sulfate aerosols. Mie scattering theory is applied to

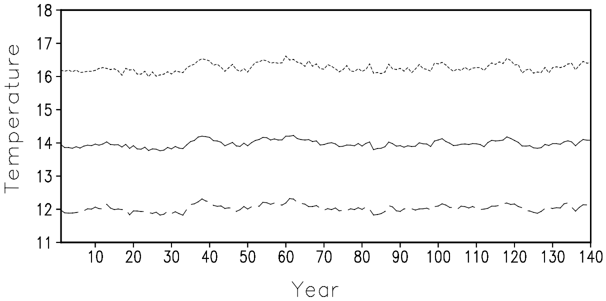

Fig. 1. The modeled global mean surface air temperature from the control experiment (annual mean: solid line; winter mean: dashed line; summer mean: dotted line, units: °C).

calculate the radiative properties including the mass extinction coefficients, single scattering albedo, and asymmetry factor (Zhang, 1999; Ma, 2002). The effect of relative humidity on the radiative properties are parameterized by using an empirical function (Kiehl and Brieglab, 1993).

3. Experimental design and data

The modified atmospheric model was re-coupled with the ocean model (Yu and Zhang, 1998), and the following four experiments were undertaken (see Table 1).

(1) Control experiment (CTL)

In this experiment, the concentrations of greenhouse gases CO_2, CH_4, and N_2O are 345 ppm, 1.743 ppm, and 0.3 ppm respectively, roughly corresponding to the level in 1985, and the concentration of industrial gases (CFC-11 and CFC-12) is zero, the concentration of sulfate aerosols is also zero; the solar constant is set equal to 1367.04 W m^{-2}. This means that the control experiment simulates the contemporary climate state.

(2) Greenhouse gases forcing experiment (GHG)

Similar to the CTL but the greenhouse gases concentration changes with time, and the concentration is taken from the historical data complied by NASA/GISS.

(3) Greenhouse gases and sulfate aerosols forcing experiment (GSD)

This experiment takes account of not only the effect of greenhouse gases, but also the direct effect of sulfate aerosols. The scheme for greenhouse gases is same as that of experiment GHG. The mass mixing ratio of the sulfate aerosols is taken from the results of a sulphur cycle model run at the Max Planck Institute in Germany (Feichter et al., 1997).

(4) Greenhouse gases, sulfate aerosols and solar variability forcing experiment (GSS)

This experiment adds the effect of solar variability to the above GSD experiment. In this work, the index of solar variability is taken as Hoyt and Shatten's solar constant data (Hoyt and Shatten, 1993), which is based on the variation of the sunspot cycle, and other historical proxy data, and is currently regarded as the one of the most reliable datasets.

Most model simulations of climate change in the 20th century have included the effects of greenhouse gases and/or direct sulfate aerosol forcing (Boer et al., 2000; Roeckner et al., 1999; Dai et al., 2001). There are few works considering the effect of solar variation. Shi et al. (1997) studied this by using a simple physical model and concluded that the effect of changes in solar irradiance on climate change over the 20th century is negligible. Tett et al. (2002) applied changes in solar irradiance estimated by Lean et al. (1995) and volcanic aerosol depth to their model to investigate the effect of natural forcings on climate. Their analysis suggests that the early twentieth century warming can best be explained by a combination of warming due to increases in greenhouse gases and natural forcing. This work includes greenhouse gases, sulfate aerosols, and solar irradiance change in the meantime into the model, which is of importance to reproduce the past climate changes.

4. Results

The control experiment involves a 140-year integration, and shows no significant climate drift (Fig. 1). The modeled global annual and seasonal mean temperatures are all similar to observations. The main characteristics of the spatial distribution of temperature is also well simulated in general, though there exists an obvious drawback at the high latitudes in the winter hemisphere where the modeled temperature has a warm bias of up to 10–20°C (Fig. 2). This is possibly

Table 1. Brief description of the four experiments.

	Greenhouse gas	Sulfate aerosols	Solar Constant
CTL	1985	No	1367.04 W m^{-2}
GHG	1900–1997	No	1367.04 W m^{-2}
GSD	1900–1997	1900–1997	1367.04 W m^{-2}
GSS	1900–1997	1900–1997	1900–1997

'No' means the concentration equals zero.

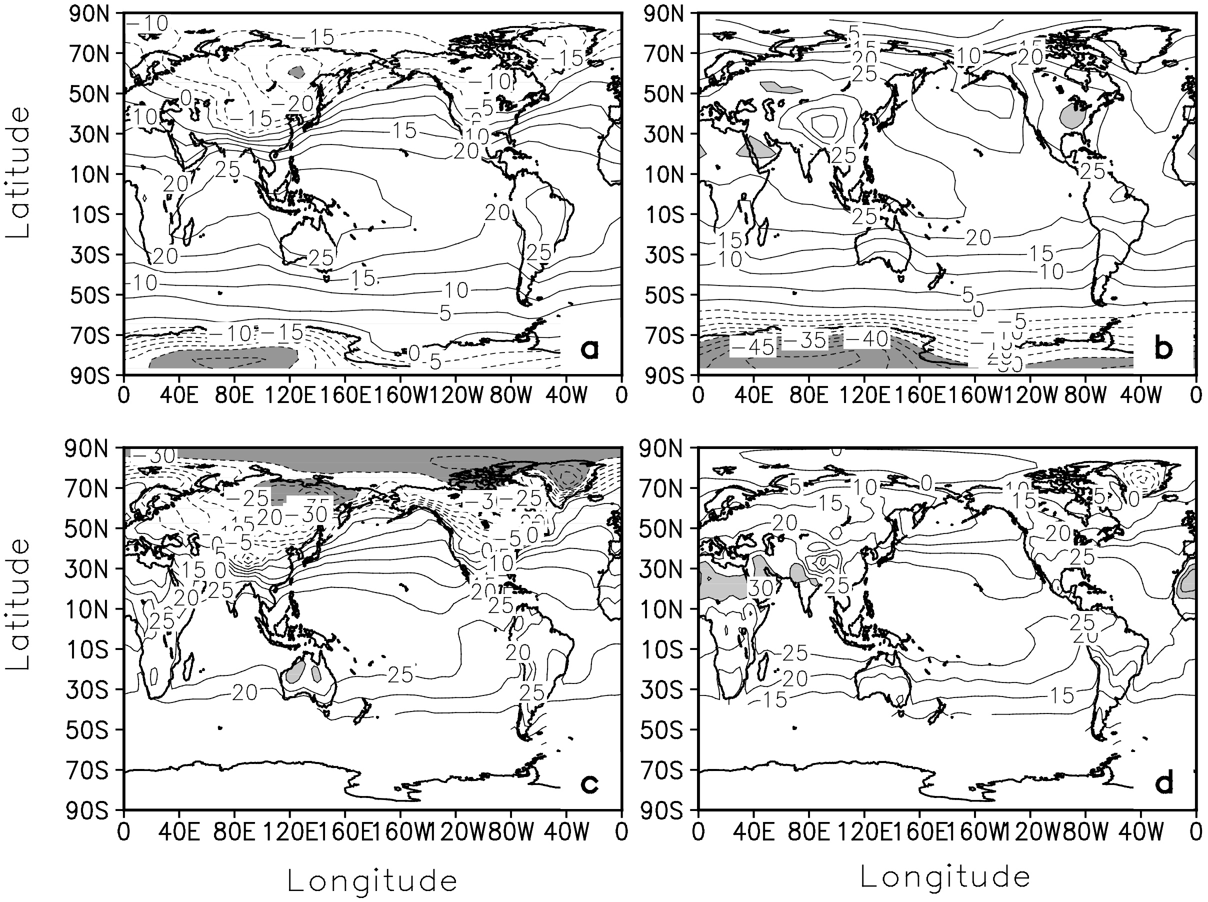

Fig. 2. The modeled surface air temperature from the control experiment and observational surface air temperature from Jone et al. (1999) (Units: °C): (a) Modled in DJF, (b) Observed in DJF, (c) Modeled in JJA and (d) Observed in JJA.

due to the errors in sea ice in the Northern Hemisphere and surface albedo over the Antarctic continent.

4.1 *Global mean temperature*

Figure 3 displays the observed global annual mean surface air temperature (Jones et al., 1999) together with results from the three forcing simulations. The curves are plotted as deviations from the 1961–1990 climatological average. The curves show a long term increasing trend together with short-term variability and the curves are similar to each other except for the warm period in the observed record during the 1920s to 1940s. There is no significant difference between three forcing experiments until the late 1980s. It is interesting to note that during some period, the simulated temperature of GSD is even larger than that of GHG though there is apparently a larger radiative forcing for GHG than GSD (Fig3.12 in Ma, 2002). This is because the effect of the greenhouse gases prior to the 1970s is not strong enough, and physical processes interact in a non-linear way, so the temperature response could fluctuate a bit. The similar phenomenon could be found in other works (Haywood et al., 1997; Boer et al., 2000; Roeckner et al., 1999). The linear trends from 1900 to 1997 are 0.977, 0.783, and 0.883°C/century for GHG, GSD, and GSS, respectively. Therefore, the warming trend in GHG is stronger than that in GSD, which indicates the effect of sulfate aerosols. Taking the effect of solar forcing into consideration, the model simulates a slightly larger warming trend than when only the effects of greenhouse gases and sulfate aerosols are included.

Table 2 lists the simulated global surface air temperature differences between 1900 and the present (the 1986–1995 mean) from GOALS and some other models (Boer et al., 2000). The increasing temperature due to the increase of greenhouse gas concentrations ranges from 0.80°C to 1.20°C, and the simulation of GOALS produces one of the three smallest temperature differences. As to the cooling effect of sulfate aerosols, the GOALS simulation is the least sensitive when com-

Table 2. GOALS simulated global annual mean surface air temperature change in the 20th century compared to the simulations from some other models. Temperature change is computed as the difference between the 1986–1995 mean and the year 1900. (Units: °C).

	GHG	GSD	GSS
CCCma	0.80	0.60	
GFDL	1.20	0.70	
MPI	0.80	0.50	
UKMO	0.90	0.50	
GOALS	0.80	0.69	0.77

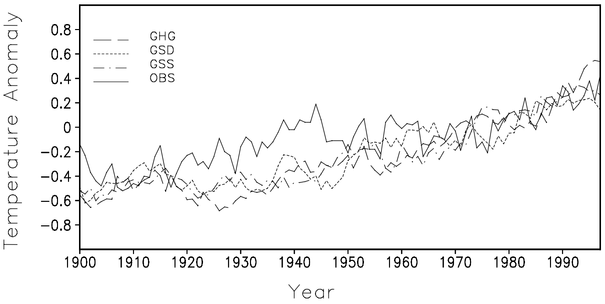

Fig. 3. Time series of modeled and observed global annual mean surface air temperature anomalies with respect to the 30-year average from 1961 to 1990 (Units: °C). The four curves are from GHG (solid), GSD (dash), GSS (dot), and observation (thick solid), respectively.

pared with the other models. Two reasons could contribute to these differences. One is the different sulfate aerosol schemes used in models. All models except MPI employ a simple sulfate aerosol scheme, which accounts for the direct scattering of sulfate aerosols by increasing surface albedo. Mitchell et al. (1995) note that such a scheme is based on three assumptions. First, the solar absorption of sulfate aerosols is negligible; second, the effect of thermal radiation is also negligible; and finally, most of the sulfate aerosols is located near the surface. Generally speaking, the first two assumptions are valid for pure ammonia sulfate. However, the last assumption could cause a 20% overestimation of sulfate scattering because the relative humidity is higher near the surface. Another reason is associated with the different sulfate burdens as the inputs into the models. This work employs the same mass mixing ratio of sulfate aerosols as MPI, so the difference between them is mainly because MPI includes both direct and indirect effects of sulfate aerosols in its model. As reported in the IPCC TAR, the indirect forcing of aerosols has a larger value when compared to the direct forcing. The use of different radiative properties in the models is also a minor reason.

The simulation from experiment GSS shows that the temperature increase is 0.77°C, which is higher than that of the experiment GSD, 0.69°C. The difference of 0.08°C between the two experiments indicates the effect of solar variability is not negligible in the 20th century climate change.

4.2 *Zonal mean temperature*

Figure 4 shows the simulated annual zonal mean temperature anomaly and its comparison with observation (Jones et al., 1999). It can be seen that the simulations from the three forcing experiments all exhibit broad agreement with observations, in particular with regard to the warming trend since the late 1970s. However, the model does not reproduce the warm anomaly from the 1920s to 1940s, which is more apparent in the Northern high latitudes. It can also be seen that the observational warming occurs as follows: the warming firstly begins in the 1920s in the northern high latitudes and continues to the 1960s with the strongest warming in the 1930s–1940s mainly in the Northern Hemisphere; later the temperatures even have a slightly decreasing trend; but the obvious warming begins in the 1980s and spreads to the whole earth with the strongest warming in the high latitudes. Compared to observations, the simulated temperature tends to a sharp increase. The obvious warming occurs in the late 1970s, and prior to this period there is no obvious warming. When including the effect of sulfate aerosols, the simulated temperatures go down slightly compared with the GHG experiment in the last two decades. There is a larger difference in the northern high latitudes between observation and the three forcing experiments, which all failed to simulate the strongest temperature increasing in the Arctic region seen in the observations. The reason possibly relates to the simulation error of sea ice in the GOALS model.

The effect of solar variation can be seen when comparing Fig. 4c and Fig. 4d. In the case which includes the change of solar radiation, the simulated surface temperature of most areas goes up by 0–0.3°C since the middle of the 1970s until the late 1990s. The warming during this period is consistent with the peak

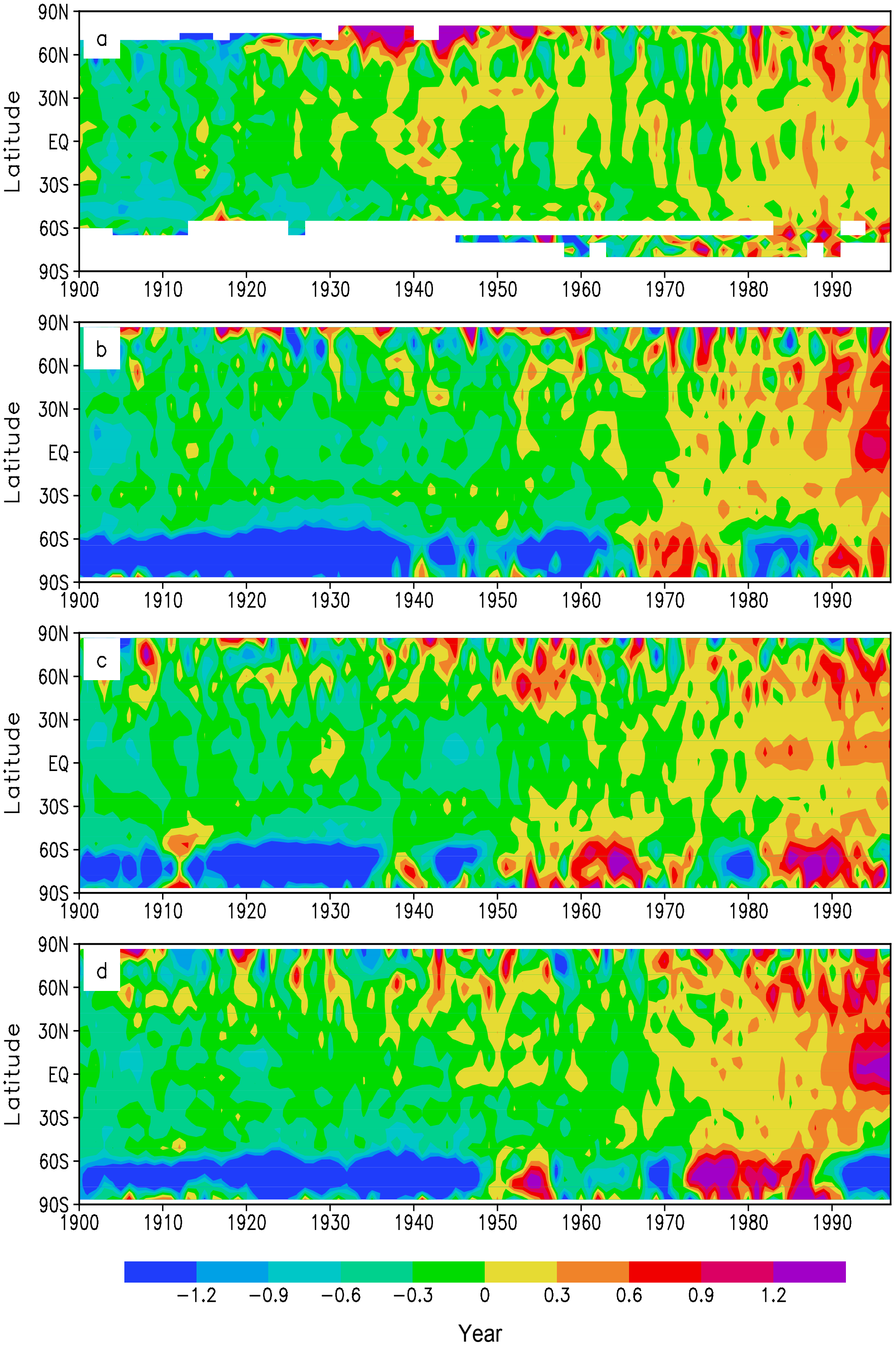

Fig. 4. Time series of zonal annually averaged surface air temperature anomalies from 1990 to 1997 relative to the 30-year average from 1961–1900. (a) Observation (from Jones et al., 1999), (b) GHG, (c) GSD, and (d) GSS.

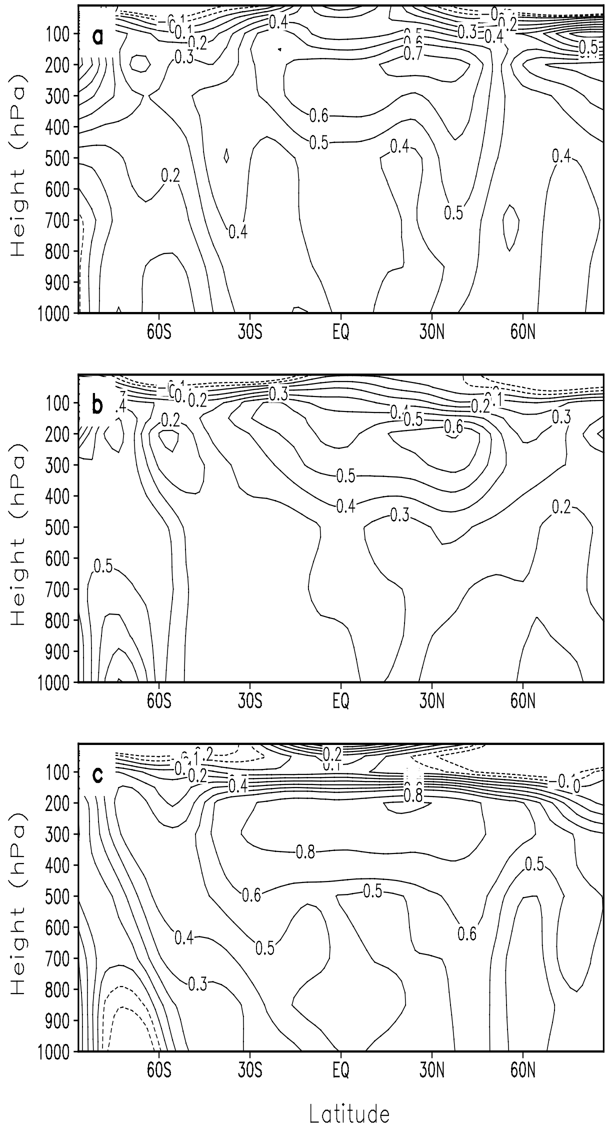

Fig. 5. The vertical distribution of te modeled temperature difference between the 1986–1995 average and the 1961–1980 average (Units: °C). (a) GHG, (b) GSD, and (c) GSS.

of solar reconstruction from the late 1970s. The solar irradiance change estimated by Hoyt and Schatten (1993) in the 20th century has two peaks, however, one of which is from the 1970s to the late 1990s and another is in the 1920s–1940s. It is clear that the model fails to simulate the warming of the earlier period in the 20th century. This is also a common problem remaining in almost all the current models (Haywood et al., 1997; Boer et al., 2000; Roeckner et al., 1999; Dai et al., 2001). A few of possibilities could explain this. For example, volcanic eruption during this time could be an important reason. So the inclusion of volcanic eruptions into the model should lead us to expect a reduction in the simulation errors at the early stage.

4.3 *Vertical temperature*

The vertical variations of temperature simulated from the three forcing experiments are presented in Fig. 5. The difference between the 1986–1995 mean and the 1961–1980 mean is used in order to make a comparison with some other results (e.g., Tett et al., 1996). The figure indicates that the GOALS model could simulate the reasonable variation of vertical temperature due to enhanced greenhouse gases, such as increasing temperature in the troposphere, decreasing temperature in the stratosphere, and the largest increase in the upper troposphere in the lower latitudes, etc. In detail, the temperature anomaly between 30°N and 30°S around 200 hPa is generally greater than 0.4°C, with a maximum value greater than 0.6°C.

Taking the effect of sulfate aerosols into consideration, we do not see a large change in the vertical distribution, but a reduction in the magnitude of the warming. With the addition of the effect of solar variability, there can be an increase in the warming, but there is little effect on the vertical structure. Compared with the observed vertical temperature change (Tett et al., 1996), the model simulates a larger temperature change in the upper troposphere, and a smaller temperature reduction in the tropical and middle latitude stratosphere.

This figure also shows us that there is the strongest warming or cooling at the high latitudes in the Southern Hemisphere. This is probably related to the simulated internal natural variability. Because there are similar characteristics in the figures from the three forcing simulations in the Antarctic (also see Figs. 4b–d), the only difference between them is that the strongest warming or cooling occurs in different years. If we take a longer time period, for example 1981–1995 (15 years) or 1976–1995 (20 years) instead of 1986–1995 (10 years), there is no strong warming or cooling anymore in these areas. So there probably exists a decadal scale natural variability at the high latitudes of the Southern Hemisphere, which means the natural variability should be removed when detecting the effect of human activity there. However, due to the considerable amount of missing data at the higher latitudes, there still remains large uncertainty.

5. Summary and discussion

The IAP/LASG GOALS coupled model is used to study the global temperature change in the twentieth century. In this work, a 140-year control experiment and three 98-year forcing experiments are conducted. The model simulates the basic characteristics of the mean climate state and its seasonal variation. The three forcing experiments indicate that the global mean surface air temperature increases by 0.80°C, 0.69°C, and 0.77°C during the 20th century for the GHG, GSD, and GSS experiments, respectively. It is obvious that greenhouse gases make the largest contribution to the global warming of the 20th century, and sulfate aerosols offset some of the warming with a global temperature reduction of 0.11°C, which is smaller than those of other models. The difference of 0.08°C between GSD and GSS shows the effect of solar variability on climate change on the global scale. The vertical distribution of temperature changes shows that there is obvious warming in the troposphere and cooling in the stratosphere; the largest warming exists at about 300–100 hPa in the upper troposphere. Sulfate and solar variability do not produce a large change in the vertical temperature structure, but do influence the warming magnitude. The major discrepancy lies in that the model fails to simulate the observed warming during the 1920s to 1940s. One reason might be the natural variability and lack of some forcing, e.g., volcanic aerosols.

In addition, only the direct effect of sulfate aerosols was considered. It is known from other work that the indirect effects may contribute a stronger radiative forcing than the direct effects (Boucher, 1995; Ghan et al., 2001; Lohmann et al., 2000). According to the latest IPCC report (2001), the indirect forcing of aerosols ranges from –0.3 W m^{-2} to –1.8 W m^{-2}, compared to the direct forcing which ranges from –0.2 W m^{-2} to –0.8 W m^{-2}. Also, volcanic aerosols and ozone in the stratosphere are of potential importance, particularly with respect to simulation of the vertical temperature structure.

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